

Assessing influence in biofuel production and ecosystem services when environmental changes affect plant–pest relationships

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Abstract

Climate change is currently affecting both biodiversity and human activities; land use change and greenhouse gas emissions are the main drivers. Many agricultural services are affected by the change, which in turn reflects on the basic provisioning services, which supply food, fibre and biofuels. Biofuels are getting increasing interest because of their sustainability potential. *Jatropha curcas* gained popularity as a biodiesel crop, due to its ease of cultivation even in harsh environmental conditions. Notwithstanding its high economic importance, few studies are available about its co-occurrence with pests of the genus *Apthona* in sub-Saharan Africa, where these insects feed on *J. curcas*, leading to relevant economic losses. Using ecological niche modelling and GIS post-modelling analyses, we infer the current and future suitable territories for both these taxa, delineating areas where *J. curcas* cultivations may occur without suffering the presence of *Apthona*, in the context of future climate and land use changing. We introduce an area-normalized index, the 'Potential-Actual Cultivation Index', to better depict the ratio between the suitable areas shared both by the crop and its pest, and the number of actual cultivations, in a target country. Moreover, we find high economic losses (~–50%) both in terms of carbon sequestration and in biodiesel production when *J. curcas* co-occur with the *Apthona cookei* species group.

KEYWORDS

agricultural economics, *Apthona cookei* species group, biofuels, climate change, ecological niche modelling, ecosystem services, GIS analysis, *Jatropha curcas*, land use change, sub-Saharan Africa

1 | INTRODUCTION

The global change is currently acting at different scales, affecting both biodiversity and human activities. The two main drivers are the increase in greenhouse gas (GHG) emissions (Shukla et al., 2019), as well as the conversion of natural areas to other uses (Ferrier et al., 2016).

The emissions are mainly due to industrial and civil activities (e.g. Breeze, 2017; Tian et al., 2016), while the

transformation of land use has several reasons, such as human and animal feeding, timber harvesting and construction of buildings and facilities, generally leading to a consequent high rate of biodiversity loss both at global and local scale (Chaudhary & Kastner, 2016; Griscom, Goodman, Burivalova, & Putz, 2018; Iannella, Liberatore, & Biondi, 2016).

The loss and/or variation of biodiversity alter ecosystem functions (a set of connected processes that are fundamental

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for the functioning of ecosystems) and a consequent loss of ecosystem services (ESs) occurs (Oliver et al., 2015). These represent the portion of conditions and processes through which the natural ecosystems and the species that compose them, support and provide services for the human well-being (Daily, 1997). ESs are divided into different categories, including regulation and maintenance services, cultural services, support services and provisioning services. The agricultural ESs fall within the provisioning services which are fundamental for the supply of food, fibres and biofuels (Carpenter et al., 2006), with these latter gaining more and more interest during last years because they represent one of the most sustainable solutions to reduce the global CO₂ increase (Quader & Ahmed, 2017).

This increase, which is one of the main phenomena responsible for global warming, is mainly due to fossil fuels use over time (Jackson et al., 2017).

One of the strategies applied for the reduction of fossil fuels' use is the production of biofuels (i.e. fuels obtained by plants) by the cultivation of non-edible vegetables, such as Madhuca (*Madhuca longifolia*), Jojoba (*Simmondsia chinensis*), Flax (*Linum usitatissimum*), Tobacco (*Nicotiana tabacum*), Tamanu (*Calophyllum inophyllum*), Physic nut (*Jatropha curcas*), etc. (Ong, Mahlia, Masjuki, & Norhasyima, 2011).

In this context, the shrub *J. curcas*, which is primarily used as a living fence around cultivations, to make soap, and as a medicinal plant (Jongh & van der Putten, 2010), gained popularity also as a biodiesel crop (Kamel, Farag, Amin, Zatout, & Ali, 2018; Parawira, 2010; Tiwari, Kumar, & Raheman, 2007). Today, many cultivations occurs, because of its suitability to be grown in bare, degraded or semi-arid areas, but even in subhumid or humid areas (Trabucco et al., 2010), reducing land reclamation and permitting to establish a carbon-storage vegetation layer in areas where forests could not establish (Burns & Nicholson, 2017). This is a crucial aspect when planning biodiesel crops, considering that the so-called 'First generation biofuels', that is, those derived from edible plants, such as maize and sugarcane, negatively impact on food production and costs, and involve significant land use changes, even at the expense of biodiversity (Börjesson & Tufvesson, 2011; Correa, Beyer, Possingham, Thomas-Hall, & Schenk, 2017; Dale, Kline, Wiens, & Fargione, 2010). Furthermore, the biodiesel obtained from *J. curcas* provides lower loads of carbon monoxide, sulphur oxides and volatile organic compounds (Pacini, Sanches-Pereira, Durleva, Kane, & Bhutani, 2014). Depending on the topography, soil profile and prevailing agroclimatic conditions, *J. curcas* can be also combined with other suitable species, comprising the agricultural, horticultural, herbal, pastoral and/or silvicultural components to result in an ecologically

viable, economically profitable and socially acceptable agroforestry system (Baumert, Khamzina, & Vlek, 2018). Because of its tolerance and ease of cultivation from tropical to semi-arid territories (Pandey et al., 2012), it is one of the best options for biodiesel production in tropical and subtropical developing countries (Thapa, Indrawan, & Bhoi, 2018).

Native to Central America, *J. curcas* is currently cultivated also in sub-Saharan Africa, China, Cambodia, Indonesia, Thailand and India (González, 2016).

In sub-Saharan Africa, where many cultures are found in the tropical and subtropical areas, phytophagous insects of the genus *Aphthona* Chevrolat (Coleoptera, Chrysomelidae, Galerucinae, Alticini) represent one of the most harmful pests of this shrub. Among them, three species of the *Aphthona cookei* species group sensu Biondi, Urbani, and D'Alessandro (2013), namely *A. cookei* (Gerstaecker), *Aphthona dilutipes* Jacoby and *Aphthona whitfieldi* Bryant, feed on leaves, leading to heavy defoliation and even the death of the plant with few hundreds of individuals, with resulting important negative impacts on local economies (Biondi et al., 2013; Sawadogo & Nacro, 2016, 2017; Sawadogo, Nagalo, Nacro, Rouamba, & Kenis, 2015).

Notwithstanding the high economic importance of *J. curcas* plantations, only some case studies about the adverse effects of *A. cookei* species group on these plants in sub-Saharan Africa were conducted by the scientific community in last years (Hartman, Pawlowski, Herman, & Eastburn, 2016; Sawadogo & Nacro, 2017). No studies are available combining the distribution of both plant and insects to obtain a more comprehensive and general trend for the future. Few studies have investigated the potential evaluation of economic gain/loss on production and ESs trade-off (Bryan, King, & Wang, 2010; Romeu-Dalmau et al., 2018), especially in the light of global change and all the possible future scenarios.

In the present contribution, we introduce an approach to: (a) locate current and future suitable territories for both taxa, (b) identify areas where *J. curcas* cultivations may occur without suffering the presence of *Aphthona* species, (c) quantify economic losses both in terms of carbon sequestration and in biodiesel production when *J. curcas* co-occur with the *Aphthona* species.

Starting from a climate-based ecological niche modelling (ENM) performed over both *J. curcas* and *A. cookei* species group in sub-Saharan Africa, we refine the models' outputs with land use-land cover (LULC) scenarios, extracting areas which are more likely to be converted to agriculture in the future based on recent literature, and assessing the potential economic value of carbon storage and biodiesel productions where *J. curcas* is likely suffer or not the co-occurrence of *A. cookei* species group.

2 | METHODS

2.1 | Target species

J. curcas L. (Euphorbiaceae) is a shrub up to 5 m high native to Central America (USDA, 2014), spread, at first by Portuguese seafarers, to Africa and Asia (Achten et al., 2008). This plant has recently shown good potential also as a feedstock for biofuel (Parawira, 2010), even though it is cultivated for many other uses because of its capability of growing in harsh conditions (Contran et al., 2013; Parawira, 2010).

Aphthona Chevrolat is a widespread flea beetle genus found in Australian, Nearctic, Oriental, Palaearctic and Afrotropical regions (Biondi & D'Alessandro, 2012). The three target species belonging to the genus *Aphthona* Chevrolat are among the most damaging pest of sub-Saharan *J. curcas* cultivations (e.g. Anitha & Varaprasad, 2012; Biondi et al., 2013; Nielsen & De Jongh, 2009), namely *A. cookei* (Gerstaecker), *A. dilutipes* Jacoby and *A. whitfieldi* Bryant (Biondi et al., 2013). Indeed, these flea beetle species feed on leaves, leading to heavy defoliation as well as the death of the plant, even with few hundreds of individuals (Biondi et al., 2013; Sawadogo & Nacro, 2016, 2017; Sawadogo et al., 2015). These three species were chosen as a unique modelling unit, considering their overlapping trophic niche, and also taking into account the morphological features and phenological cycles, as suggested by the application of the 'lumping' approach by Smith, Godsoe, Rodríguez-Sánchez, Wang, and Warren (2019) and references therein.

2.2 | Target species data set and study area

To perform the ENM process, the records for the target species *J. curcas* (both native and study area, as usually performed for modelling species outside their range (e.g. Cerasoli, Iannella, & Biondi, 2019; Iannella, D'Alessandro, & Biondi, 2020; Iannella, D'Alessandro, Longo, & Biondi, 2019) and useful to improve model performance (Broennimann & Guisan, 2008)) were collected by integrating GBIF occurrences and presence localities from published resources, for a total of 4,305 occurrence localities for *J. curcas* (GBIF, 2019) and a total of 60 occurrence localities for *A. cookei*, *A. dilutipes* and *A. whitfieldi* (hereafter *Aphthona* spp.; Biondi et al., 2013; M. Biondi, personal data); about *J. curcas* occurrences, data for both the native range (Central America, following USDA, 2014) and the African range (our study area) were downloaded and considered.

Duplicate records were discarded using the 'Topology validation' tool in ArcMap 10.0 (ESRI, 2010). To avoid any spatial correlation between the remaining presence localities, a partial removal of the occurrences was performed through the 'spThin' package (Aiello-Lammens, Boria, Radosavljevic, Vilela, & Anderson, 2015) in environment R (R Core Team, 2016),

setting the thinning parameter to 10 km and 10 replicates. After the thinning process, a Moran test was performed ('Spatial autocorrelation tool' in ArcMap, ESRI, 2010) to further assess possible correlation among presence localities. The data set used for the analyses is reported in Table S1. The study area is sub-Saharan Africa, where the two target taxa both occur.

2.3 | Ecological niche modelling

To predict distribution for the two target taxa, a set of seven bioclimatic variables was used following the choice of Trabucco et al. (2010), which were in turn selected by these authors after both a jackknife procedure (to discard variables providing no additional information in the models they performed) and a correlation matrix-based procedure (to select one variable for any pair exceeding Pearson's correlation > 0.85). Furthermore, we found these variables to be congruent with the rearing conditions used in literature (Sawadogo & Nacro, 2016), as well as with the in situ observations of *Aphthona* spp. annual life cycle (Sawadogo et al., 2015). In particular, Trabucco et al. (2010) found *J. curcas* to be influenced by the mean annual temperature (with an optimum between 26°C and 27°C) and a minimum temperature of the coldest month, which must be above 8°C–9°C to positively affect this plant. Moreover, precipitation-related suitability was found optimal at 2,000 mm/year, even though this species can tolerate higher values of humidity (Trabucco et al., 2010).

Similarly, *Aphthona* was found to have an optimum in growth and reproduction for medium-high temperatures (25°C ± 3°C) and humidity = 65% ± 5% (Sawadogo & Nacro, 2016).

In this paper, we selected the same variables used by Trabucco et al. (2010), namely BIO1 (mean annual temperature), BIO2 (mean diurnal range), BIO5 (maximum temperature of the warmest month), BIO6 (minimum temperature of the coldest month), BIO12 (annual precipitation), BIO13 (precipitation of the wettest month) and BIO15 (precipitation seasonality), downloaded at 2.5 arc-minutes resolution from the online repository Worldclim.org, version 1.4, for the 'current' climatic conditions (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). To obtain ENMs for the future climatic conditions, two Representative Concentration Pathways (RCPs) were chosen, the 4.5 and the 6.0; these represent two of the four the different possible trajectories of the GHG in the future, in terms of radiative forcing, adopted by the IPCC in its fifth assessment (Taylor, Stouffer, & Meehl, 2012). Indeed, we chose these two RCPs also considering that they are more likely to occur, with respect to the 2.6 ('very stringent') and 8.5 ('business as usual') pathways, thus giving us the possibility to address practical management advices

and plausible estimates of ESs and their corresponding monetization. To reduce uncertainties due to the differences in different General Circulation Models (GCMs) available (Stralberg et al., 2015), three different GCMs were chosen for the 2050 RCP 4.5 and 6.0 scenarios, the CCSM4 (Gent et al., 2011), the IPSL (Marti et al., 2010) and the MIROC-CHEM (Watanabe et al., 2011).

ENM were built in R environment (R Core Team, 2016), using the 'biomod2' modelling package, which permits to obtain the so-called 'Ensemble Models' (EMs), the models obtained by merging single ENMs calculated by the different algorithms available within (Thuiller, Georges, & Engler, 2016). The 'BIOMOD_EnsembleModeling' function was used for this purpose, with single models obtained from Generalized Linear Models (set to type = 'quadratic' and interaction level = 3), Multiple Adaptive Regression Splines (set to type = 'quadratic' and interaction level = 3), Generalized Boosting Models (sometimes named BRTs, with number of trees set to 10,000, interaction depth = 3 and 10-fold cross-validation) and Maxent (Maxent.Phillips, maximum interactions = 5,000 and betamultiplier = 2), an approach often used to encompass and take advantage of different modelling techniques (Cerasoli et al., 2019; D'Alessandro, Iannella, Frasca, & Biondi, 2018; Iannella, D'Alessandro, & Biondi, 2018). Five sets of 1,000 pseudoabsences each were generated through the 'sre' (Surface Range Envelope, set to 0.05) algorithm, which calculates a linear envelope on the basis of selected predictors and selects pseudoabsences outside the set quantile, for all the reasons reported in Iannella, Cerasoli, D'Alessandro, Console, and Biondi (2018) and all the references within.

Both the Area Under the Curve (AUC) of the Receiver Operating Characteristics curve (Phillips, Anderson, & Schapire, 2006) and the True Skill Statistics (TSS; Allouche, Tsoar, & Kadmon, 2006) were used as indicators of single models' discrimination performance. About 80% of each data set was used for model calibration, while the remaining 20% for its evaluation. Considering that five iterations were performed (NbRunEval = 5) for each set of pseudoabsences (=5) and for each of the four modelling technique, a total of 100 single models were finally obtained; EMs were built by using only single models exceeding both the AUC > 0.80 and TSS > 0.70, so as to select the best performing models. The weighted mean of probabilities ('wmean') algorithm was chosen as the main result of the ensemble modelling process, because of its capability of weighting, when merging together, every single model on the basis of the respective performance score (Thuiller et al., 2016; Thuiller, Lafourcade, Engler, & Araújo, 2009). The 'BIOMOD_EnsembleProjection' was subsequently used to project the calibrated models to the two different timeframes considered (2050_4.5 and 2050_6.0) for each GCM chosen. Considering the differences in GCMs (and, thus, in the

projections obtained for the same future scenario), particular attention was given to model extrapolation (i.e. the possible differences between the predictors' values used for model calibration and the ones used in models' projections; Elith & Leathwick, 2009). To deal with this issue, the Multivariate Environmental Surface Similarity (MESS; Elith, Kearney, & Phillips, 2010) was calculated to map extrapolation areas, through the 'mess' function of 'dismo' R package (Hijmans & Elith, 2016). This spatial information was used to calculate the Multivariate Environmental Dissimilarity Index (MEDI; Iannella, Cerasoli, & Biondi, 2017) and applied to down-weighting extrapolation to the future EMs.

2.4 | Postmodelling analyses

ENM obtained from the aforementioned processes were further analysed in GIS environment, so as to refine the predictions in more plausible distribution scenarios of both target taxa (Iannella, De Simone, D'Alessandro, Console, & Biondi, 2019).

We performed the future simulations of land use–land cover (LULC) in sub-Saharan Africa and created a carbon storage model through the InVEST suite, a geospatial modelling framework tool which evaluates the impact of land use change on ESs (Sharp et al., 2018).

Also, we assessed the possible value (in USD) of carbon storage and biodiesel services produced by *J. curcas* alone and when co-occurring with *Aphthona* spp., in all these different future scenarios.

The basic LULC we chose for all the analyses performed is the 2018 Global Land Cover, in the framework of the Copernicus Climate Change Service, which classifies land surface into 22 classes at a spatial resolution of 0.002778° (~300 m).

2.4.1 | Future LULC scenario simulation

To obtain simulations of future landcover, the 'Scenario Generator proximity based' (SGpb) of the InVest suite (Sharp et al., 2018) was used; this tool allows to create simulations of alternative possible futures using user-defined principles.

When translating policies into planning, it is often important to refer to 'guidelines' (or 'storylines') and examine how they can be quantified into spatial data; for this purpose, the Shared Socioeconomic Pathways (SSP) narratives future quantitative data by Riahi et al. (2017) were used. This SSP database (SSPdb) was created to model and compare future possible trajectories of both LULC and climate scenarios (deriving from the RCPs), as well as to quantify these changes.

The mitigation scenarios within our data set were built to provide a link between the SSPs and the RCPs, so as to

use SSPs information in conjunction with the RCPs chosen for future climate projections; thus, the SSPx-4.5 and SSPx-6.0 scenarios were chosen, and the future variations of the 'Croplands' LULC type were selected.

Considering that the SSPdb is divided in five regional aggregations, a proportion was made with the FAOSTAT Crops database (FAO, 2015) to extract the values of our study area (sub-Saharan Africa) from the Middle East and African countries region (R5.2MAF in the SSPdb). This analysis showed that sub-Saharan Africa represents the 77.61% of the R5.2MAF aggregation of the SSPdb.

We considered the Croplands variation in million hectares for two SSPs narratives: SSP2 and SSP3. In the SSP2 (middle of the road), the change in land use is incompletely regulated, that is, tropical deforestation continues, although with slow declining rates; crop yield rates slowly increase over time (Fricko et al., 2017).

The second SSP narrative considered, SSP3 (regional rivalry), shows a resurgent nationalism, concerns about competitiveness and security, and pushes countries to increasingly focus on domestic or regional issues. Land use change is hardly regulated, rates of crop yield strongly decline over time, especially due to very limited transfer of new agricultural technologies to developing countries (Fujimori et al., 2017).

To obtain the values to properly set the SGpb, the variation (2020 ÷ 2050) between the present and future agricultural areas was calculated for each SSP.

To simulate future LULC we applied the two SSP projections to the croplands in the LULC classes more likely to be changed (see below), nearest to the existing croplands. Three types of landcover were chosen: (a) 'Focal landcover' (SGpb tool converts classes from the edge of patches of focal landcovers) was chosen based on the most likely categories to increase the agricultural areas. It is more likely to expand agriculture from existing crops than to create new ones. (b) 'Convertible landcover' represent the landcover types which can be converted, chosen based on the classes which have changed more in the past 20 years, and obtained from the analysis of these LULC variations (ESA, 2017). (c) 'Replacement landcover' was chosen because the agricultural landcover class is the one which showed to be the most frequently converted in, with respect to the other LULC categories.

2.4.2 | ES—Carbon storage and biodiesel value

To carry out the carbon storage model, we used the carbon model tool of the InVest suite (Sharp et al., 2018). The ES 'carbon storage' was selected for its importance, among all ESs, to land use changes. A global 2018 LULC map (ESACCI-LC-L4-LCCS-Map-300m-P1Y-2018-v2.0.8) was

clipped for the study region and reclassified based on the Land Cover Classification System (Di Gregorio, 2005).

The InVest model handle a simplified carbon cycle that maps and quantifies the amount of carbon stored (and sequestered) based on four carbon pools: above-ground biomass, below-ground biomass, soil and dead organic matter (Sharp et al., 2018).

Using average values from Leh, Matlock, Cummings, and Nalley (2013), which are to date the best estimates for Africa matching with the aforementioned 2018 LULC map, we estimated the carbon stored in each carbon pool for each land use category, by considering three carbon pools: above-ground biomass, underground biomass and organic carbon in the soil. The carbon in each pool was subsequently aggregated to provide estimates of the carbon stored in the whole landscape.

To calculate the carbon storage value, we used the economic projections of the social value of carbon in Nordhaus (2017). The social value of carbon in Africa in 2015 was 1.03 \$/tCO₂. We used a 5% discount rate (as specified in Nordhaus, 2017) per year to calculate future values (2020 and 2050).

The biodiesel potential value was calculated by using literature data concerning the African context. About the monetary value of *J. curcas* oil, the cost of US\$ 0.99/L proposed by Ofori-Boateng and Lee (2011) was considered, while we considered the average value of 2,700 L ha⁻¹ year⁻¹ proposed by Fang (2013) for calculating the yield per hectare.

Based on these values, we inferred the amount in US\$ of the land use categories intersected by *J. curcas* resulting for the medium-high and high suitability classes. We assumed that the price of *J. curcas* biodiesel and the yield of cultivated crops remained constant over time, because, currently, no projections to future are available for of these data.

2.4.3 | GIS analysis on current and future LULC simulations and ecological models

To infer areas of co-occurrences for the MEDI-corrected models, we polygonized and intersected them with the simulations of current (LULC_2018) and future LULC scenarios (LULC_2050_SSP2_4.5, LULC_2050_SSP2_6.0, LULC_2050_SSP3_4.5 and LULC_2050_SSP3_6.0).

The resulting spatial data were intersected with the current and future Carbon storage models (Carbon_2018 and Carbon_2050_SSP2_4.5, Carbon_2050_SSP2_6.0, Carbon_2050_SSP3_4.5, Carbon_2050_SSP3_6.0, respectively), so as to estimate economical values of stored carbon.

Furthermore, to evaluate the co-occurrence between target taxa within each sub-Saharan country (for the most relevant trends obtained by our analyses), we calculated a 'doubled' ratio index. This index, called here 'Potential-Actual Cultivation

Index' (PACI), consists of the ratio between the intersection of suitable areas of for the two target taxa (belonging to a single country) and the number of actual cultivation projects in the country (Gexsi, 2008); the result of this first ratio is normalized by further dividing it by the total area of the country.

3 | RESULTS

The generated data set resulted in 2020 occurrence records for *J. curcas*, in both its native and study area (sub-Saharan Africa), and 60 occurrence localities for the three *Aphthona* spp. (Figure 1). The Moran's test performed over both the two data sets (of which the one belonging to *J. curcas* was thinned to 1,028 presence points) shows that no spatial correlation is found for each, with Moran's $I = -0.001$ (expected value = -0.002), z -score = 0.386 and $p = .699$ for *J. curcas* and Moran's $I = -0.0008$ (expected value = -0.0004), z -score = -0.849 and $p = .395$ for the *Aphthona* spp. data set.

The ENMs show good discrimination performance, with a TSS = 0.869 and AUC = 0.864 for *J. curcas* and TSS = 0.880 and AUC = 0.961 for *Aphthona* spp. The three most contributing variables for *J. curcas* are BIO13 (precipitation of the wettest month) = 34.6% of the total contribution, BIO6 (minimum temperature of the coldest month) = 33.1% and BIO12 (annual precipitation) = 20.5%, while BIO6 = 33.5%, BIO15 (precipitation seasonality) = 21.9% and BIO12 = 20.3% are the ones most contributing for the *Aphthona* spp. The marginal response curves built for the two shared variables (BIO6 and BIO12) show a similar trend with respect to the

response of both taxa to these two predictors, with a peak for *Aphthona* spp. between 10°C and 20°C, and an increase in suitability for *J. curcas* over 10°C, and a peak for both taxa at about 1,000 mm of annual precipitation (Figure S1).

The three suitability classes obtained from the ENM calibrated on the current climatic conditions for *J. curcas* show a continuous highly suitable area in the sub-Saharan territories, with a large patch with medium suitability in Central Africa connecting two other highly suitable patches, one in the western and (a large) one in the eastern side (Figure 2). The highest number of *J. curcas* plantations are generally hosted by countries with high suitable territories (with respect to the total extent of the country area), such as Tanzania, Uganda and Benin, even though some exceptions are found (e.g. Central African Republic) (Figure 2).

When comparing the three suitability classes for both *Aphthona* spp. and *J. curcas*, the sub-Saharan Africa 'splits' into two zones, in the northern part of the study area—a belt in which the suitability for *Aphthona* spp. is low and the one for *J. curcas* is medium or high (i.e. plantations are in a climatically unsuitable area for *Aphthona* spp.), and some large patches in which both have climatically suitable areas available (Figure 3). Also, two main patches in Central Africa with low suitability for *Aphthona* spp. and high (or medium) suitability for *J. curcas* are predicted, while a large area (and some minor and scattered patches) is found in Eastern Africa, where both taxa have high suitable areas (Figure 3).

These climate-predicted co-occurrences are compared with *J. curcas* plantations, which currently fall for more than 65% into areas with high or medium suitability for the three

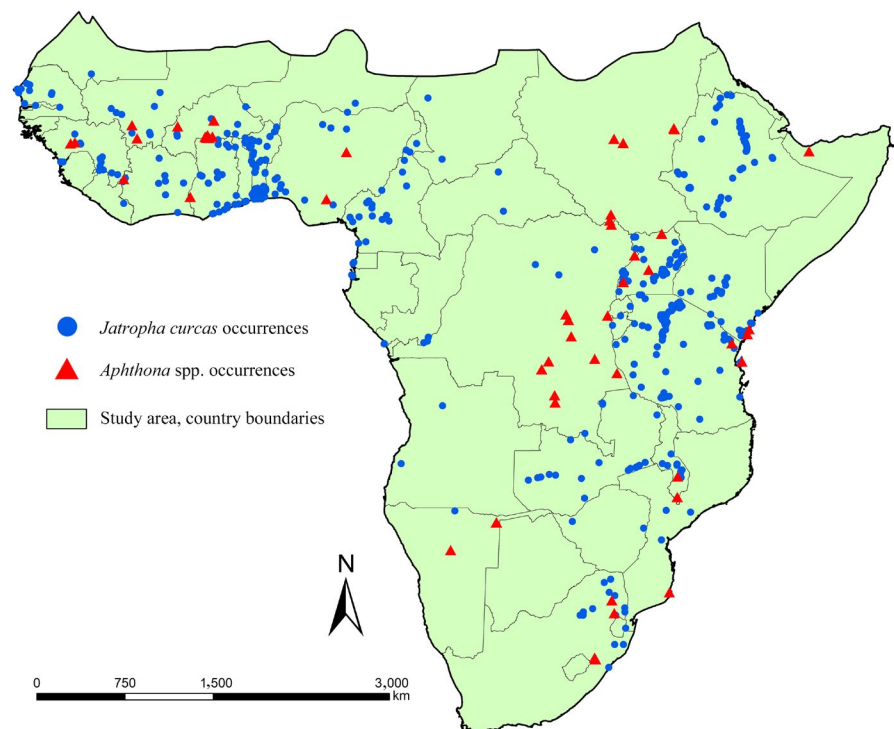


FIGURE 1 Occurrence localities in sub-Saharan Africa for the two target taxa. Presence points of *Jatropha curcas* (blue dots) and *Aphthona* spp. (red dots) sub-Saharan Africa (see text)

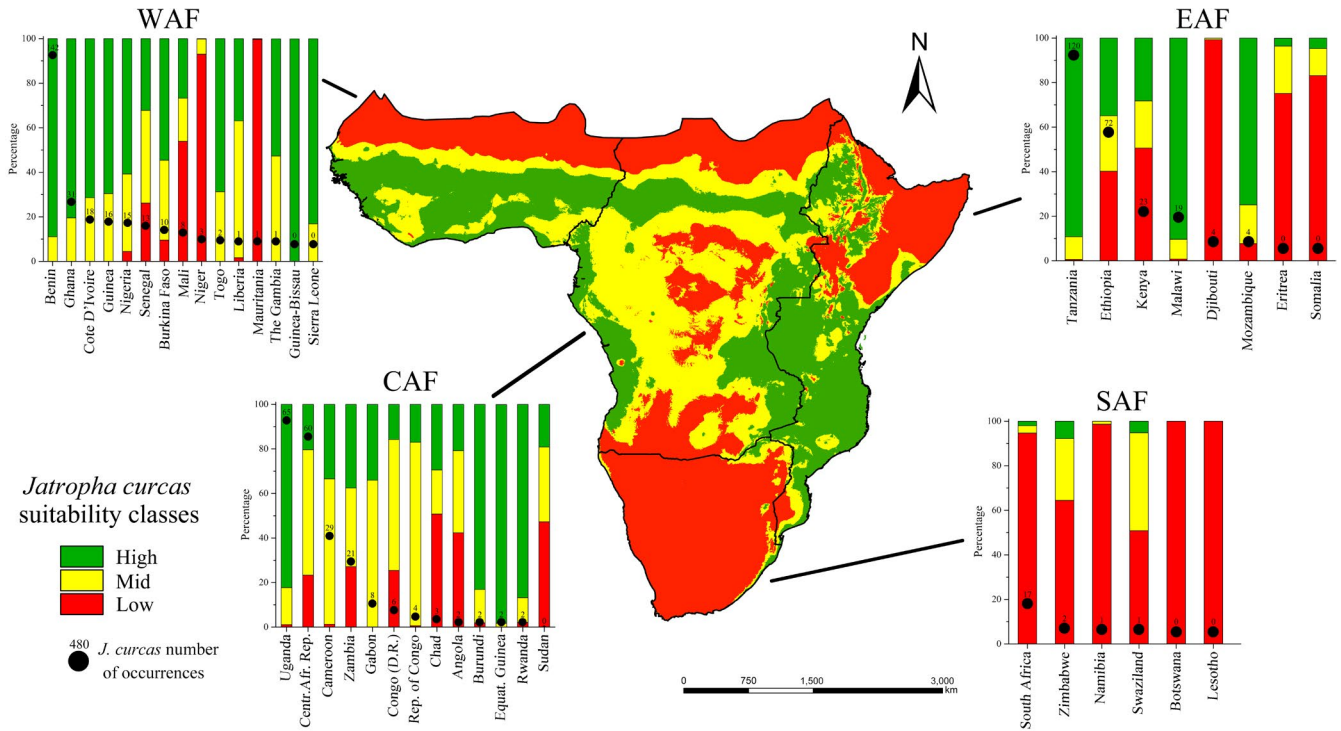


FIGURE 2 *Jatropha curcas* suitability classes. Spatial distribution of suitable areas (Low: 0–0.33, red; Mid: 0.33–0.66, yellow; High: 0.66–0.99, green) obtained from the ecological niche modelling on current climatic conditions for *J. curcas*, the percentage of the three suitability classes with respect to each sub-Saharan country extent in Western (WAF), Central (CAF), Eastern (EAF) and Southern (SAF) Africa. In black dots, the number of localities in which *J. curcas* occurs per country

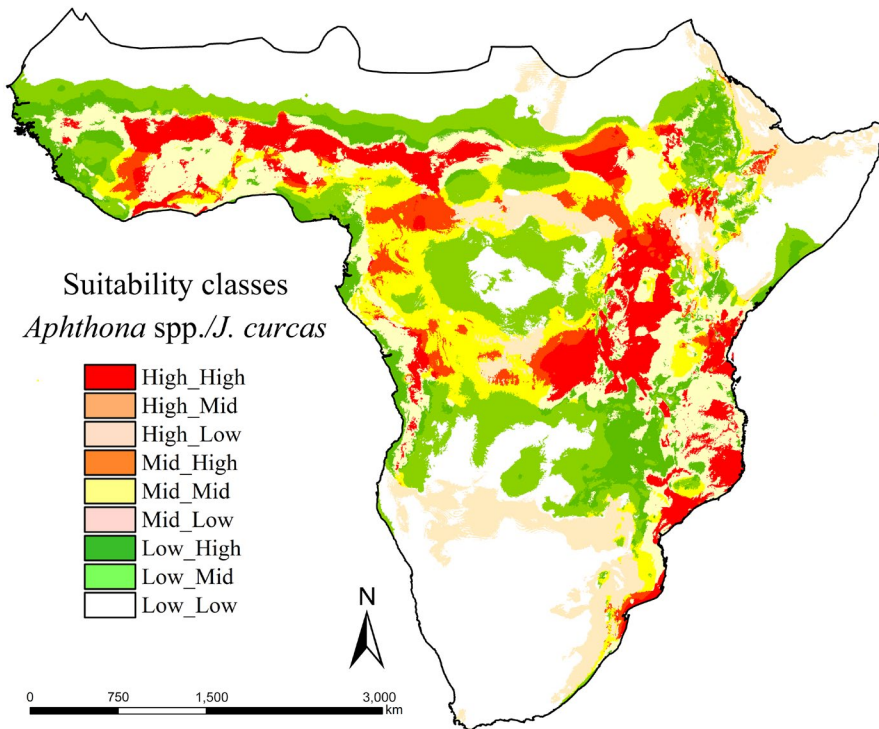
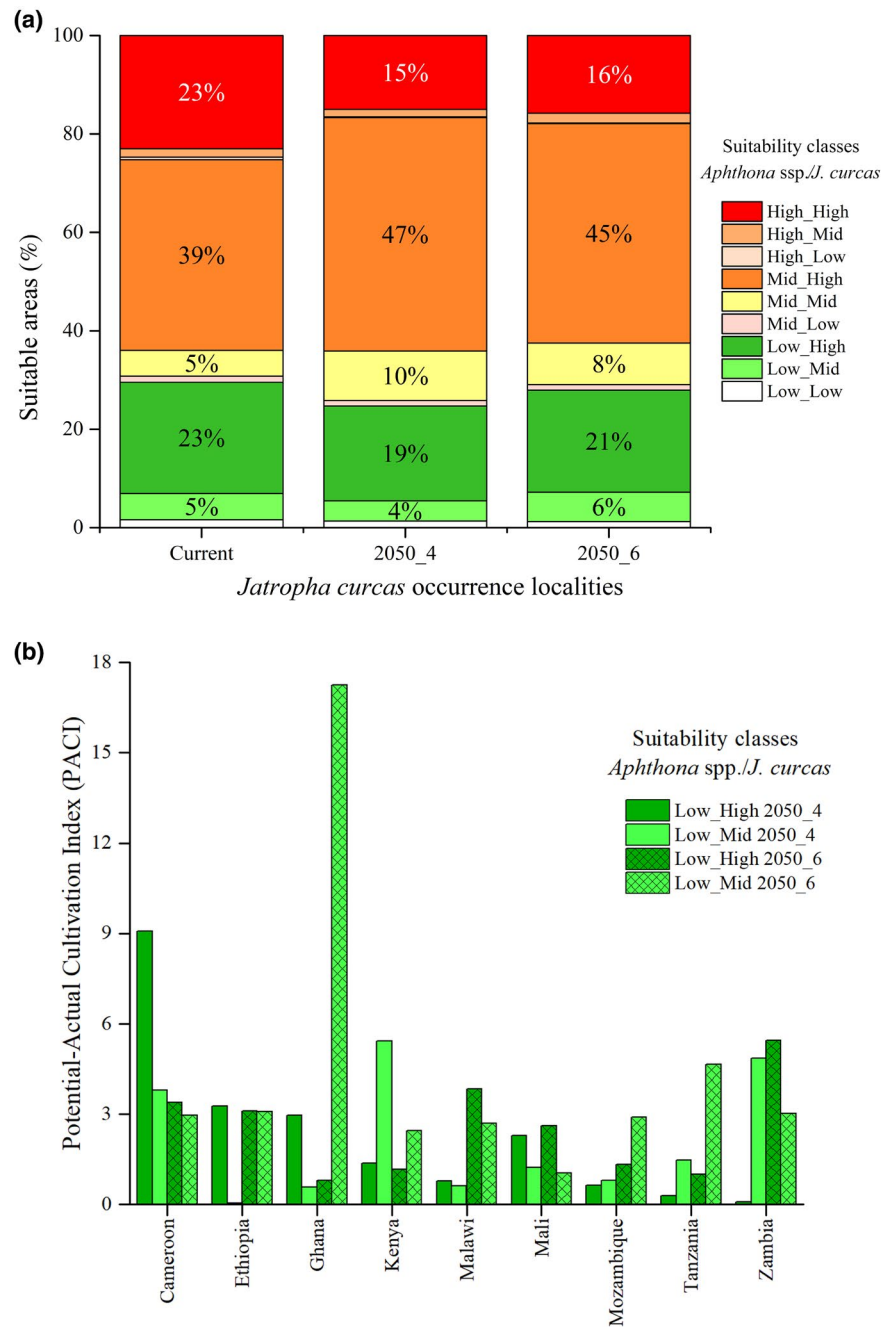


FIGURE 3 Overlap of suitable areas for *Aphthona* spp. and *Jatropha curcas*. Co-occurring suitable areas inferred through ecological niche modelling for the current climatic conditions for both *Aphthona* spp. and *J. curcas*

flea beetle species considered (Figure 4a). In the future climatic scenarios, with the plantations of *J. curcas* considered as fixed, an increase of both *Aphthona* spp. and *J. curcas*

medium suitability classes is predicted for them, at the expense of the higher classes of the two; all the other co-occurrence classes remain stable (Figure 4a).

FIGURE 4 (a) Percentage of *Jatropha curcas* occurrences in territories of overlapping climatic suitability of *Apthona* spp. and *J. curcas*; (b) PACI index calculated for the most relevant countries. (a) Localities of *J. curcas* (considering its occurrences as fixed for the future scenarios) falling within the different co-occurrence predicted areas for *Apthona* spp. and *J. curcas* in current and future scenarios; (b) ratio between the potential suitable areas and the number of *J. curcas* occurrences, normalized per area of each country (PACI), calculated for the most relevant countries hosting positive conditions for the growing of *J. curcas*



The most relevant trends highlighted from this analysis, in terms of countries involved, were further analysed by using the PACI (Figure 4b).

Considering the land use change scenarios (SSP 2 and 3) in the context of climate RCP trajectories (4.5 and 6.0) and the corresponding territories overlapping suitability classes of *J. curcas*, an increase is observed for all the combined scenarios for high suitable areas of *J. curcas* (Figure 5). This analysis reports that the suitability of *J. curcas* varies considerably in the different land use simulations. In the low suitability class, *J. curcas* shows a relevant negative variation in the SSP2 LULC simulations for both the 4.5 and 6.0 mitigation scenarios, while a strong, positive

variation is observed in both the SSP3 simulations (4.5 and 6.0), with percentage increasing nearly to the 100% if compared to the current scenario.

About the medium class, *J. curcas* seems to maintain a stable trend with variations in the 'Cropland - rainfed' land use classes, ranging from approximately -50% to $+20\%$ in SSP2 simulations. A relevant increase is found in the other agricultural classes ('Cropland-irrigated or post-flooding' and 'Mosaic croplands'), where these are mostly affected by the presence of *J. curcas*. The trend tends more towards the 'Cropland-rainfed' class in the SSP3 simulations, where in both mitigation scenarios a positive variation is observed (over 50% compared to the 'Current'; Figure 5).

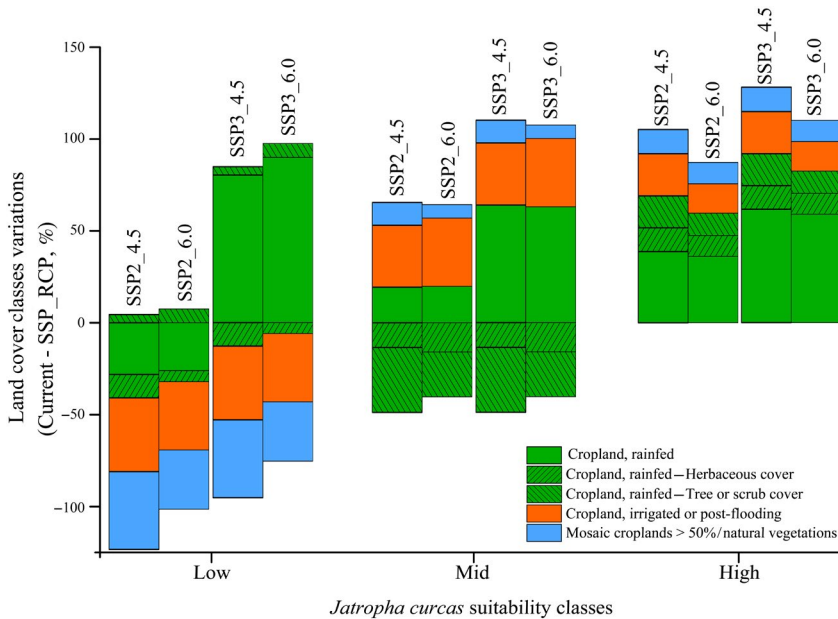


FIGURE 5 Area variation of Land cover classes within *Jatropha curcas* predicted suitable areas. Variation of land cover classes considered for the two different SSP narratives (sensu O'Neill et al., 2017) and Representative Concentration Pathways (RCPs) overlapping the three different suitability classes inferred for *J. curcas* current climatic conditions

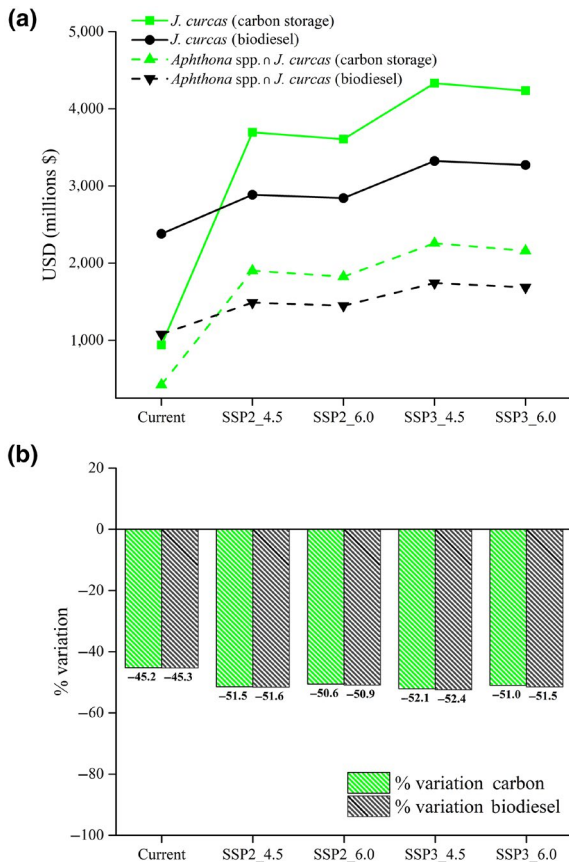


FIGURE 6 (a) Inferred value (USD, millions per year) of ecosystem services provided by *Jatropha curcas* alone (solid line) and *J. curcas* co-occurring with *Aphthona* spp. and (b) variation in these values (per cent) for all the future scenarios considered. (a) Economic value of the carbon storage (green) and biodiesel (black) produced by *J. curcas* alone (solid line) and when co-occurring with *Aphthona* spp. (dashed line), in the current and the future different coupled land use–Representative Concentration Pathway scenarios considered; (b) percentage of variation of economic value calculated on the co-occurrence scenarios

The highest climatic suitability for *J. curcas* (High class) shows a positive variation with respect to 'Current' for all simulations of land use change (SSP2_4.5–6.0 and SSP3_4.5–6.0). In all the scenarios, the trend towards the 'Cropland-rainfed' class remains higher while a decrease for the other two land use classes ('Cropland-irrigated or post-flooding' and 'Mosaic croplands') is observed (Figure 5).

For the current scenario, a total of 937 million \$ was calculated for *J. curcas* carbon storage; where the target taxa overlap, a value of 424 million \$ was calculated. By contrast, the monetary value of potential biodiesel production of 2,378 million \$ was obtained for *J. curcas* only, while in the overlapping areas the value lowers to 1,077 million \$.

The presence of *J. curcas* in the future LULC simulation 2050-SSP2 4.5 (small expansion of croplands) shows monetary values for carbon storage and potential biodiesel production at around 4 billion \$ and 3 billion \$ respectively. In the other future scenario 2050-SSP2 6.0 (lower expansion of croplands), the monetary value of the services offered by the *J. curcas* was found to slightly drop (Figure 6a). About the 2050-SSP3 4.5 (maximum expansion of the croplands) and 2050-SSP3 6.0 (large expansion of croplands) scenarios, the values of the services offered increased by over 4 billion \$ in the first scenario, reaching about the same value in the second scenario (Figure 6a). It is evident that both in the current and future scenarios, the overlap with *Aphthona* negatively impacts the economic values of the services offered by *J. curcas*, showing an average 50% of negative variations (Figure 6b).

4 | DISCUSSION

Development agencies in sub-Saharan Africa supported pilot projects for decentralized rural energy supply. Today,

relevant investments related to the cultivation of *J. curcas* as an energy crop are taking place, although strong regional disparities occur. As resulting from the GEXSI report (Gexsi, 2008), West Africa has a long tradition in the cultivation of *J. curcas* to be used as a pure vegetable oil for the energy supply in villages. As documented by the aforementioned report, large-scale projects have occurred in several countries such as Ghana, Mali, Nigeria and Cameroon; in East Africa the major projects are reported in Tanzania and Ethiopia, but there are also small-scale projects in Uganda and Kenya. Moreover, the GEXSI report (Gexsi, 2008) accounts also for the southern part of the African continent, where the most ambitious projects are nowadays developing in Angola, Botswana, Zambia and Mozambique.

In accordance with the GEXSI report (Gexsi, 2008; which designates the areas previously mentioned, as well as where there are the largest projects concerning plant target species), our analyses show that the climatic suitability in the current scenario for *J. curcas* is mainly found in two districts: Western (WAF) and Eastern (EAF) Africa. Also, the Central African (CAF) district shows medium and high levels of climatic suitability, with a large area of medium suitability towards the western coast (Figures 1 and 2). In these territories, the largest number of *J. curcas* plantations occur mainly in Tanzania, Uganda and Benin, although some exceptions are found, such as the Central African Republic, where the crops occur in the central-east side (Figure 2). In these territories, the co-occurrence analysis highlighted the potential susceptibility of *J. curcas* cultivations to *Apthona* spp., as also reviewed by Jingura and Kamusoko (2018) for sub-Saharan Africa. In fact, areas located in Sahel and Eastern Africa, suitable for *J. curcas*, are more likely to be inhabited also by *Apthona* spp., thus resulting in a high number of patches where the plants might suffer severe damages (Figure 3).

In the future scenarios, if considering that *J. curcas* current plantations will remain in the same localities, *Apthona* spp. suitable territories with medium and high suitability are predicted to increase, co-occurring with the plantations. In the 2050_4.5 climate scenario, the most relevant increase is observed in the Mid_High (*Apthona*-*J. curcas*) class, whereas the most favourable class for *J. curcas* cultivations (Low_High class) yields a decrease from the current to the 2050_4.5 scenario. In this scenario the crops of *J. curcas* will have to deal with a constant presence of *Apthona* spp. (Mid class) which could potentially lead to a decrease in yield productivity (Figure 4a). The 2050_6.0 climate scenario showed a similar trend but with a slight increase in the Low_High co-occurrence class and a decrease in the classes where the presence of *Apthona* spp. is more pronounced (Figure 4a).

The postmodelling analysis reveals that the overlap of the suitability models between the two target taxa indicates a relevant trend in the Low_High (*Apthona*-*J. curcas*) and Mid_High (*Apthona*-*J. curcas*) classes.

In both climatic scenarios analysed, the Low_High class shows a positive future response trend in some countries such as Mali, Cameroon, Angola and Zambia. The Mid_High class (the most represented in the global trend) represents a relatively negative situation for *J. curcas* crops, since the constant presence of *Apthona* spp. can potentially lead to the complete destruction of the crop. The analysis carried out per country shows that this class follows a similar trend in both climatic scenarios. The influence of *Apthona* spp. will be more pronounced over some countries (e.g. Ghana, Ethiopia, Kenya, Tanzania, Zambia, Malawi and Mozambique) where large *J. curcas* cultivation projects occur.

The PACI shows different and specific trends for some local situations. In the 2050_4.5 climate scenario, the most 'positive' situation (Low_High) is observed in Cameroon, while in the 2050_6.0 scenario, the most favourable condition for raising *J. curcas* occurs in Zambia. Similarly, the most negative situation (Mid_High) in the 2050_4.5 climate scenario is found in Kenya and Zambia, whereas the 2050_6.0 scenario reveals the most unfavourable condition in Ghana, which shows the absolute highest value (PACI = 17.25) among all those obtained from this analysis (Figure 4b). These countries will face a wide potential spread of *Apthona* spp. on *J. curcas* which, if not slowed down, will likely cause high economic loss.

The mitigation scenarios used (SSPs) to achieve the emission reduction targets often show a substantial contribution from bioenergy, in particular as a fuel in the transport sector or as a raw material for energy production (possibly in combination with the capture and carbon storage; Daioglou et al., 2017).

However, bioenergy production is often associated with land use modification, which leads to changes in carbon reserves related to the soil surface and because of the subsequent emissions. These have important consequences on the effectiveness of reducing GHG emissions, while LULC could also have negative implications for biodiversity and food production. In this case, *J. curcas* crops represent a good compromise between energy production and carbon storage, which is why the approach used in this study took both factors into account.

About all medium suitability classes, a decrease is inferred for two rainfed croplands (herbaceous and tree or scrub cover), while a decrease for all land use categories is predicted for the low suitable territories in the SSP2 (both 4.5 and 6.0 RCPs), even though an exception is observed for the tree- or scrub-covered rainfed croplands (Figure 5). The SSP3 scenarios resulted in a decrease of irrigated, mosaic and tree- or scrub-covered rainfed croplands, with a concurrent great increase of rainfed croplands (Figure 5).

The analysis showed that the 'Cropland-rainfed' class is the most suitable land use category for the cultivation of *J. curcas* in accordance with Basinger et al. (2012), but

in the future, the crops of *J. curcas* could expand (due to the medium suitability of the target plant) on agricultural classes that need artificial irrigation or on agricultural mosaics if the SSP2 scenarios were to occur. This will depend above all on the political decisions that determine the choices in the energy and food security field (Winter, Faße, & Frohberg, 2015; Figure 5). However, the spatial resolution of LULC simulations and ENMs models is relatively coarse, therefore this study focused on larger world region where the simulations can be improved by detailed local studies.

As revealed from the analysis of co-occurrence between *J. curcas* and *Apthona* spp., in future land use simulations these insects will contribute to harm the productivity of biofuel crops, leading to a huge economic loss for the sub-Saharan countries. For this reason, in the present analysis, we have considered the economic aspect, both for ESs (carbon storage) and for that deriving from the production of biodiesel.

As observed for many plants which are linked to economic interests (Naik, Goud, Rout, & Dalai, 2010), in the near future the attack from pests, is likely to cause very high economic impacts, also because of the link with the energetic compartment. Furthermore, in the near future, more interest will be given to carbon sequestration, because of ongoing and future strategies aiming at removing the CO₂ from the atmosphere (Shukla et al., 2019).

Our application to the involved economic aspect showed a great difference between the monetary values obtained for Carbon storage and Biodiesel production (Figure 6).

In the current scenario, the monetary loss for both services offered by *J. curcas*, due to the overlap with *Apthona* spp., drops significantly with percentage values around -45%. On the other hand, in the future simulations, the greatest negative variation (-52%) is observed in the SSP3_4.5, which shows peculiar characteristics regarding CO₂ emissions and land use change. The analysis shows how the co-occurrence between the two target groups is detrimental for services offered by *J. curcas*' crops both in the different climatic and land use change scenarios. The results show that the monetary value of the carbon storage ES will exceed that of biodiesel production in future scenarios. Consequently, both the environmental and the strictly economic benefits will be strongly affected by the co-occurrence with *Apthona* spp., causing potential damage of several billion dollars. This is likely to happen if the *J. curcas* future 'new' crops (as well as for the current ones) will be established without following scientific criterion as performed to date (Ahmed & Gasparatos, 2016).

However, the possible effects of further biofuel requests on national food production and international trade are not considered in the present study and need to be assessed for specific countries' future policies.

The integrated use of ENM, land use simulations and models for the assessment of ESs, as performed in our study,

has shown to offer some advantages in the study of the potential distribution of pests on crops of economic interest. This approach allows to evaluate the potential spread of harmful organisms on crops before and during practical management, focusing economic efforts on strategies for specific areas.

The categorization of climatic preferences helps to highlight the landcover areas of particular interest for the species that infest the crops and allows to provide an economic assessment, reducing the uncertainties deriving from a single ENM-based approach.

The approach used in this study, although being coarse, given the spatial resolution of the data, allows a very accurate analysis of the distribution of the target taxa and a preventive economic evaluation useful to prevent the implementation of these economic crops where the climatic conditions are not suitable. This saves investors time and money and allows you to apply targeted actions on any type of economic crop.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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